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Direct Use of Satellite Horizontal Gradients in Variational Analysis

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Introduction: It all began during the International H_2O Project (IHOP 2002). We compared derived GOES water vapor data against in-situ GPS IPW measurements and discovered alarming discrepancies with GOES-11 and GOES-8 used during the exercise that focused on the central plains. It was discovered that GOES data were moist biased and appeared to have the best match to RAOBs and GPS data at synoptic times. However, at asynoptic times this agreement worsened. Since there was not way for us to modify the bias in the product directly at that time, the former Forecast Systems Laboratory looked at ways to assimilate the data to ignore bias. This was accomplished by assimilating gradient structure only.

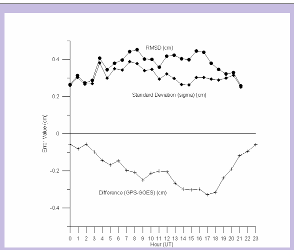


Figure 1. Shows the asynoptic variability of GOES moisture product data when differenced against GPS IPW data at co-located sites during IHOP 2002. The result showed a high periodicity with the best agreement at synoptic times. Until this research there was no independent comparison of the product data at asynoptic times. This was our first insight that the GOES product synoptic error measures were not representative at all hours.

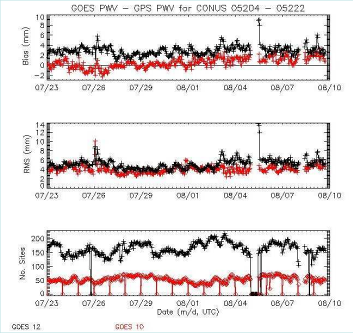


Figure 2. Work continued through the summer of 2005 both on the product itself and we also examined GOES-10 data and were surprised to find that it was superior to GOES-12 for reasons speculated to be the drier conditions in the western part of the CONUS.

$$J = S_{SAT}\sum_{k=1}^{7}\frac{\mathrm{GT}(g_i)[\mathrm{R}(T,cq,o_3)_i - R_i^o]^2}{E_{SAT}^2} + \sum_{i=1}^{N}\frac{(1-c_i)^2}{E_{BACK}^2}$$
$$+ S_{GPS}\frac{\left(\sum_{i=1}^{N} c_i q_i - Q^{GPS}\right)^2}{E_{GPS}^2 L_{GPS}} + S_{sonde}\frac{\sum_{i=1}^{N}\left[\mathrm{RH}(T,p,cq)_i - RH_i^o\right]^2}{E_{sonde}^2 L_{sonde}}$$
$$+ S_{GVAP}\sum_{j=1}^{3}\frac{\mathrm{G}(g)[\sum_{i=1}^{N}\mathrm{P}_{ji}(c_i q_i) - Q_j^{GVAP}]^2}{E_{GVAP_j}^2 L_{GVAP}} + S_{CLD}\sum_{i=1}^{N}\frac{\mathrm{g}_i[c_i q_i - q_s(t_i)]^2}{E_{CLD}^2}$$

Figure 3. The above equation shows the earlier functional used to minimize the moisture solution in the LAPS analysis. Each term represents a data source and the circled term represented the assimilation of the GOES product data. Since the advent of GOES-8 the assimilation was accomplished by directly using the GOES generated values in the product as it was assumed that bias was low and stable. As noted above, this was discovered to be incorrect.

$$J = S_{SAT}\sum_{k=1}^{7}\frac{\mathrm{GT}(g_i)[\mathrm{R}(T,cq,o_3)_i - R_i^o]^2}{E_{SAT}^2} + \sum_{i=1}^{N}\frac{(1-c_i)^2}{E_{BACK}^2}$$
$$+ S_{GPS}\frac{\left(\sum_{i=1}^{N} c_i q_i - Q^{GPS}\right)^2}{E_{GPS}^2 L_{GPS}} + S_{sonde}\frac{\sum_{i=1}^{N}\left[\mathrm{RH}(T,p,cq)_i - RH_i^o\right]^2}{E_{sonde}^2 L_{sonde}}$$
$$+ S_d S_{GVAP}\sum_{j=1}^{3}\frac{\mathrm{G}(g)[\sum_{i=1}^{N}\frac{\Delta}{\Delta x}\mathrm{P}_{ji}(c_i q_i) - \frac{\Delta}{\Delta x}Q_j^{GVAP}]^2}{E_{xGVAP_j}^2 L_{GVAP}}$$
$$+ S_d S_{GVAP}\sum_{j=1}^{3}\frac{\mathrm{G}(g)[\sum_{i=1}^{N}\frac{\Delta}{\Delta y}\mathrm{P}_{ji}(c_i q_i) - \frac{\Delta}{\Delta y}Q_j^{GVAP}]^2}{E_{yGVAP_j}^2 L_{GVAP}}$$
$$+ S_{CLD}\sum_{i=1}^{N}\frac{\mathrm{g}_i[c_i q_i - q_s(t_i)]^2}{E_{CLD}^2}$$

Figure 4. The proposed new functional that now replaces the GOES product term (GVAP) with the derivative counterpart. The derivative in the variational scheme guarantees no bias and increased structure. The problem that remained was the determination of the partial derivative weighting coefficients for the new functional. The circled equations are the partial derivatives that replace the direct use of the data in Figure 3.

The following analytic testing was used to determine the weights applied to the new functional by simulating an inferior background and "perfect" satellite gradients based on "truth". An assessment of error was then applied to the analyzed result directly differencing it with "truth."

$$Truth\ \ data = T = T(x,y)$$

$$T(x,y) = 12.5\,[\sin(x\frac{\pi}{4}) + \sin(y\frac{\pi}{4})] + x^2 + y^2$$

$$\frac{\partial}{\partial x}T(x,y) = 12.5\frac{\pi}{4}\cos(x\frac{\pi}{4}) + 2x$$

$$\frac{\partial}{\partial y}T(x,y) = 12.5\frac{\pi}{4}\cos(y\frac{\pi}{4}) + 2y$$

Satellite gradient data

Inferior function

$$Background = B(x,y) = x^{1.8} + y^{1.8}$$

The following functional was then minimized numerous times to minimize the 'p' function. Each run used a different set of "C" coefficients to produce the best error as defined below. The results of the applied coefficients are shown in Figure 5.

$$J = c_1[p(x,y)B(x,y) - B(x,y)]^2 + c_2[p(x,y)B_x^{'}(x,y) - T_x^{'}(x,y)]^2$$
$$+ c_2[p(x,y)B_y^{'}(x,y) - T_y^{'}(x,y)]^2$$

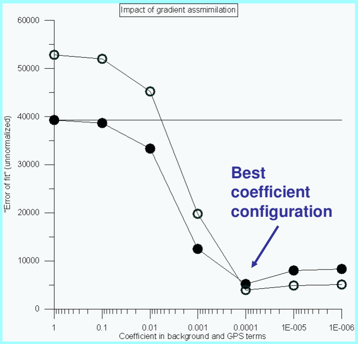
$$A(i,j) = p(i,j)B(i,j)$$

$$Error = \sum_{i=5}^{46}\sum_{j=5}^{46}[T(i,j) - A(i,j)]^2$$

Figure 5. The synthetic "error" results after applying different weights to the synthetic data presented earlier. A sharp reduction on the order of ~90% error was obtained when applying the satellite gradient data alone.

The open circles represent the addition of synthetic GPS data spaced at roughly every 100km (the analysis grid was 10km). Further reduction is observed including GPS data at asynoptic times along with the GOES data.

The results of this exercise demonstrated that the gradient weights need to be on the order of 10^4 greater than the coefficients on the non-gradient terms to achieve the best result.



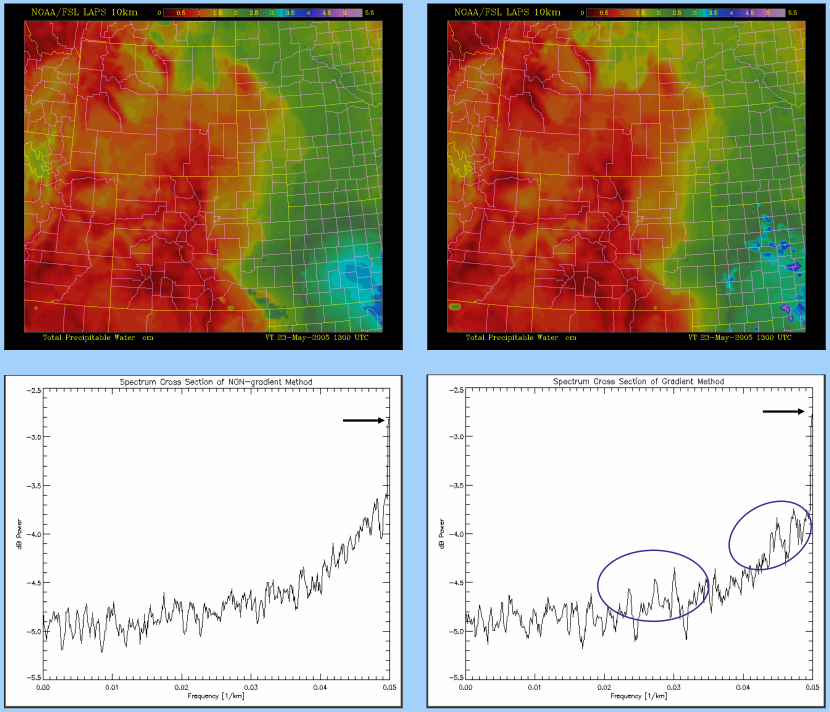


Figure 6. The old assimilation scheme (left) compared with the new assimilation scheme (right). Less moisture is seen in the new scheme and the spectral analyses beneath each indicate the new scheme contains more structure.